which align with the upstream end of each leg segment (or angle) of the surface feature grooves. The CFD simulation results for cases 4 and 5 in Table X2 suggest that this surface feature geometry is flow direction dependent, with cis-B flow direction developing a well mixed flow somewhat more quickly, and the cis-A flow being bi-furcated in the main channel, although both cases show good mixing. As with the cis cases in Table X1, results from both case 4 and case 5 (Table X2) show the bulk of the flow in the main channel is pulled toward those those lateral positions across the main channel width which align with the upstream end of each leg segment (or angle) of the surface feature grooves, and there are no cores of flow which are not periodically swept into the surface features as they travel down the length of the main channel.

Summary of Effect of Feature Geometry

[0312] Two aspects of surface feature geometry which are important for providing good mixing within the main channel bulk flow are:

[0313] 1) The surface features must effectively induce a fraction of the bulk flow in the channel to turn into the leading edge of each surface feature, and

[0314] 2) maintaining a sufficient feature run length between local upstream and downstream extremities or "ends" of each surface feature for a sufficient number of repeated surface features, repeated along the flow length. The sufficient run length is preferably at least twice the channel gap, and more preferably a minimum of 4 times the channel gap.

One variable important to inducing flow within the surface features is the surface feature depth ratio, R_{depth}:

$$R_{depth} = \frac{depth_{SF}}{\text{gap}}$$

where $depth_{SF}$ is the depth of the surface feature and gap is the gap in the main channel. In order to induce sufficient flow to enter the surface features, the surface feature depth to channel gap ratio, R_{depth}, is preferably in the range 0.010 to 100, more preferably in the range 0.10 to 10, and more preferably in the range 0.25 to 2.

[0315] The lateral spread between local upstream and downstream extremities in all surface features along a stretch of channel containing the same surface feature geometry which repeats along the flow length is defined by the lateral spread ratio, $R_{lateral\ spread}$. The lateral spread ratio is defined as:

$$R_{lateral\ spread} = \frac{\text{extremity\_length}_{SF} \cdot \cos(\alpha)}{span_{SF}}$$

where $\text{extremity\_length}_{SF}$ is the length of a surface feature leg from the local upstream extremity to the local downstream extremity, α is the surface feature angle, and $span_{SF}$ is the span of the surface feature. Note that in the extreme of $\alpha=90°$ (which is a surface feature aligned with the main channel mean bulk flow direction) the lateral spread ratio is zero. In order to be effective at penetrating the bulk flow, the lateral spread ratio should be preferably in the range 3 to 100, and more preferably in the range 5 to 20. Note that having an appropriate lateral spread ratio is a necessary but not sufficient condition to cause significant penetration of the bulk flow by surface feature induced flow effects.

[0316] The number and spacing of surface features when continuously repeated in the flow direction are also important. The spacing from feature to feature is preferably less than the $\text{extremity\_length}_{SF}$ and more preferably within a ratio of 0.1 to 10 of spacing length to the surface feature span, and even more preferably as close as reasonably possible, which may be dictated by fabrication limitations. The minimum number of surface features which should be repeated to establish good mixing depends on the geometry and conditions, but a simplified rule of thumb is to design the channel with an appropriate surface feature entrance length. In other words, we can define a feature entrance length number ($L_{feature\ entrance}$) as:

$$L_{feature\ entrance} = \frac{depth_{SF} \cdot N_{SF} \cdot N_{featured\ walls}}{\text{gap}}$$

where $depth_{SF}$ is the depth of the surface feature, gap is the gap in the main channel, N_{SF} is the minimum number of continuously repeated substantially similar surface features per wall, and $N_{featured\ walls}$ is the number of walls containing surface features. In order to establish a good mixing pattern, the feature entrance length number is preferably 5-80, and more preferably 10-40, and still more preferably 10-20. Of course, beyond the feature entrance length, more features than the minimum number may be continuously repeated, but the feature entrance length gives an estimate of the minimum number needed to establish flow patterns which bring fresh bulk flow from the main channel into the active surface features assuming other aspects of the design (such as main channel gap) do not preclude this.

Example

Thermal Reactions

[0317] Surface features are anticipated to be advantageous for homogenous reaction, including both catalyzed and uncatalyzed reactions. An example of an uncatalyzed homogeneous reaction is the thermal cracking of ethane to ethylene.

[0318] The use of surface features induces mixing or flow rotation in a microchannel and thereby breaks the laminar streamlines. In a traditional laminar flow microchannel a substantial gradient in temperature exists from the channel centerline to the wall. For endothermic reactions, the centerline temperature is much cooler and thus the overall rate of reaction is reduced. For exothermic reactions, the centerline temperature is much higher and thus the formation of unwanted side reactions may be exacerbated. The flow rotation within the channel reduces the temperature gradients within the channel. In addition, a much higher heat transfer coefficient along with more surface area to transfer heat at the wall of the microchannel is created with wall surface features. Heat can thus be more quickly added to the process microchannel for endothermic reactions or more